The Epidemiologic Transition Revisited: Compositional Models for Causes of Death by Age and Sex

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FOR MORE THAN three decades, researchers have examined the links between demographic and socioeconomic changes and systematic shifts in disease and mortality patterns (Frederiksen 1969; Omran 1971; McKeown 1976; Preston 1976; Bulatao 1993). Omran (1971) first used the term "epidemiologic transition" to characterize these regular transformations in the cause composition of mortality, by which pandemics of infectious diseases are gradually replaced by chronic, degenerative diseases as the leading causes of death. The focus of the theory of epidemiologic transition, according to Omran, is on "the complex change in patterns of health and disease *and* on the interactions between these patterns and their demographic, economic and sociologic determinants and consequences" (p. 510; italics in original).

Since Omran, a number of writers have sought to refine or extend the notion of the epidemiologic transition, for example by examining the complex linkages between changes in cause-of-death patterns and changes in morbidity (Johansson 1991, 1992; Riley 1992; Murray and Chen 1992). A broader notion of the "health transition" has been introduced to account for response of the organized health system to long-term changes in the health conditions of a society (Frenk et al. 1989b; Caldwell et al. 1990). The concept of the epidemiologic transition has been used to analyze the experience of a number of countries (e.g., Omran 1977; Schooneveldt et al. 1988; Wolleswinkel-van den Bosch et al. 1997; Frenk et al. 1989a). Some researchers have challenged the view of the epidemiologic transition as a universal theory of unidirectional change, emphasizing heterogeneity in the pace or quality of the transition in different settings (Fetter et al. 1995; Murray and Chen 1994) or pointing to examples of "counter transitions" (Frenk et al. 1989a; Gaylin and Kates 1997).

Beginning with Preston (1976), the regularity of the epidemiologic transition has been formalized in models that seek to explain the composition of all-cause mortality as a function of the level of all-cause mortality. In addition to providing interesting formalizations of the epidemiologic transition, cause-of-death models have been used to estimate cause-specific mortality in regions of the world where all-cause mortality rates are known, for example from demographic surveys, but where information on cause-specific mortality is incomplete or missing (Murray and Lopez 1997; Bulatao 1993).

In this article, we present new cause-of-death models that are based on World Health Organization data on mortality by age, sex, and cause recorded by vital registration systems from 1950 to the present. The analysis makes use of more robust statistical models for compositional data than those used previously and incorporates per capita income levels in order to present a richer view of the epidemiologic transition that captures the interactions between demographic and socioeconomic change. The aim is to examine empirical regularities in the composition by cause of mortality by age and sex since 1950, and to consider whether the theory of the epidemiologic transition presents a durable framework for understanding more recent patterns relating causes of death to overall levels of mortality from all causes.

The theory of the epidemiologic transition

Following the notion of the demographic transition, which was used to explain population growth based on changes in fertility and mortality, Omran's 1971 essay sought to elucidate the determinants and consequences of changing patterns of mortality. The basic premise of Omran's theory was that, in progressing from high to low mortality levels, all populations experience a shift in the major causes of illness and disease. Whereas infectious diseases and nutritional and reproductive health problems predominate in high-mortality populations, chronic and degenerative diseases predominate in low-mortality populations.

The model proposed by Omran identifies three sequential eras. The first era, called the "age of pestilence and famine," is marked by high and fluctuating mortality rates and a life expectancy at birth between 20 and 40 years. During the second era (the "age of receding pandemics"), mortality declines steadily, life expectancy rises to around 50 years, and sustained population growth begins. Mortality eventually stabilizes at low levels during the third age, that of "degenerative and man-made diseases," when cancers, cardiovascular diseases, and accidents emerge as the major causes of death.

Following the publication of Omran's original essay, extensions to the three-stage model have been proposed by Omran and others (Omran 1982; Olshansky and Ault 1986; Rogers and Hackenberg 1987; Vallin 1993). One of the most influential expositions was presented by Olshansky and Ault (1986), who observed unexpectedly rapid declines in chronic disease mortal-

ity rates in the United States and elsewhere starting around 1970, and therefore postulated a fourth stage in the epidemiologic transition. During the "age of delayed degenerative death" described by Olshansky and Ault, cause-of-death patterns by age remain stable, but mortality from degenerative diseases shifts toward older ages as a result of rapidly declining death rates.

One issue that has inspired considerable debate is the question of the universality of the epidemiologic transition. Omran himself distinguished three variants of the basic pattern: the classical, or Western model; an accelerated model characteristic of Japan; and a contemporary, or delayed model that applies to ongoing transitions in developing countries. Although Omran briefly discussed variation in patterns of transition by age and sex, his analyses were presented mostly at the population level. Subsequent examinations of subpopulation variation in mortality declines have noted important differentials, for example between males and females (Preston 1976; Retherford 1975; Waldron 1993) or between different race groups (Ruzicka and Kane 1990).

Another critique of the theory has emphasized deviations from the general pattern of linear, unidirectional change. Frenk et al. (1989a, b), reporting on the experience of Mexico, have pointed to the occurrence of "counter transitions," in which age-specific mortality rates rise rather than fall over time. One of the most notable examples of a counter transition is the HIV/AIDS pandemic in sub-Saharan Africa (Gaylin and Kates 1997), but other historical examples include a period of rising mortality rates for males over age 35 in France between 1850 and 1900 (Anderson 1955), increases in adult male death rates in Eastern Europe between 1952 and 1985 (Uemura and Pisa 1988; Eberstadt 1989), and rising adult male mortality in Nauru, attributable largely to accidents, cardiovascular diseases, and diabetes mellitus (Taylor and Thoma 1985; Schooneveldt et al. 1988).[1]

Amid questions as to whether the theory of the epidemiologic transition represents a universalizing concept, one of the most enduring lessons from the model of the transition is the notion of a systematic relationship between the level of mortality from all causes and the relative composition of causes that contribute to this overall level. In addition to Omran, there have been several other influential proponents of this idea. For example, two years before the publication of Omran's essay, Frederiksen (1969) delineated specific patterns of disease characterizing various levels of mortality. He postulated endemic infections, parasitisms, infestations, and nutritional deficiencies in high-mortality populations being replaced by bronchopulmonary and cardiovascular diseases, malignant neoplasms, mental illness, accidents, and obesity in low-mortality populations.

Elsewhere, McKeown's classic works on the history of mortality change in England and Wales (1976, 1979) provided a longitudinal examination of changes in causes of death over nearly a century. McKeown computed the proportion of the decline in standardized mortality rates due to specific

causes. Three-fourths of the decline in mortality was due to the reduction in infectious diseases; the remainder attributable to noninfectious causes was mostly in the category of nephritis, diseases of early infancy and old age, and other diseases. Over the same period, age-standardized mortality rates for cardiovascular disease increased by 250 percent, and rates for neoplasms increased nearly fourfold.

Cause-of-death models

Preston models

Following the same arguments that gave rise to informal analyses of changing cause-of-death patterns by Frederiksen, Omran, and McKeown, the idea that epidemiologic transition theory is first and foremost a description of the systematic relationship between mortality levels and cause composition rather than a linear description of universal change over time has inspired efforts to characterize this systematic relationship formally.

Using historical vital registration data for industrialized countries and a few developing countries, Preston (1976) presented the first comprehensive statistical models relating total mortality and cause-specific mortality. Preston analyzed life tables for 43 national populations, including long historical sequences for developed countries such as the United States and England and Wales compiled by Preston, Keyfitz, and Schoen (1972). Included in Preston's 1976 analysis were life tables for nine developing countries: Chile, Colombia, Costa Rica, Guatemala, Mexico, Panama, Taiwan, Trinidad and Tobago, and Venezuela. Cause-specific age-standardized death rates for 11 broad groups of causes were related to the overall age-standardized death rates among males and females separately, using linear regression equations of the following form:

$$M_i = \beta_0 + \beta_1 T_i + \varepsilon_i \qquad (1)$$

where M_i is the cause-specific mortality rate in observation i, T_i is the total mortality rate, β_0 and β_1 are fitted coefficients, and ε_i is a normally distributed error term.

The estimated slopes in Preston's regression equations represent the proportionate contribution of each cause to a unit change in the total mortality rate. Except for neoplasms in both sexes and cardiovascular diseases in males, all of the estimated slopes were positive and significant, indicating that mortality rates from each specific cause were expected to decline as total mortality declined. The major causes accounting for declines in overall mortality in these data were influenza, pneumonia, and bronchitis (contributing 24 to 28 percent of the decline); respiratory tuberculosis (11 to 12 percent); diarrheal diseases (10 to 11 percent); and other infectious and parasitic diseases (14 to 15 percent). With regard to the two exceptions to

the generally positive associations between cause-specific and all-cause mortality (neoplasms and cardiovascular diseases), Preston observed that both of these causes were inversely correlated with the residual category of "other and unknown causes." Under the hypothesis that this residual category may have included deaths from neoplasms or cardiovascular disease that were misclassified, Preston recomputed the models including "other and unknown" as an independent variable and found that the negative association was reversed.[2]

Preston's work has formed the basis of most subsequent approaches to modeling cause-of-death patterns. Typically, later refinements have involved estimating equations for specific age groups, incorporating more recent data, or examining more detailed causes. Hakulinen and colleagues (1986) extended Preston's approach by estimating the relationship between cause-specific mortality and overall mortality for specific age groups. Using Preston's database and 1980 vital registration data from the World Health Organization, they estimated the total number of deaths from each of Preston's 11 cause groups for major world regions.[3] Several other efforts have also built on Preston's original work (e.g., Bulatao 1993; Hull 1981; Lopez and Hull 1983; Murray, Yang, and Qiao 1992).

Global Burden of Disease study 1990

One of the most detailed examples of cause-of-death models was presented by Murray and Lopez (1996) in the Global Burden of Disease 1990 study (GBD 90). In much of the original work on the epidemiologic transition, the main division of causes was between infectious and parasitic diseases on the one hand, and noncommunicable diseases on the other. In the GBD study, causes have been divided at the broadest level into three groups (see Table 1): communicable, maternal, perinatal, and nutritional diseases (Group 1), noncommunicable diseases (Group 2), and injuries (Group 3). Group 1 includes maternal causes, diseases of early infancy, nutritional deficiencies, and acute respiratory infections along with traditional infectious and parasitic diseases such as diarrhea, helminthic diseases, malaria, and tuberculosis. All of the causes in Group 1 decline at much faster rates than overall mortality and account for a small proportion of deaths in industrialized countries. Group 2 (the noncommunicable diseases) includes neoplasms, endocrine disorders, blood diseases, cardiovascular diseases, chronic respiratory diseases, skin and subcutaneous diseases, nervous system disorders, musculoskeletal diseases, congenital anomalies, and symptoms and signs of senile and ill-defined conditions. The diseases in Group 2 are the most important health problems in populations that have undergone or almost completed the epidemiologic transition. Deaths caused by injuries, including both intentional (suicide and homicide) and unintentional injuries, constitute Group 3. Injury death rates tend to be most variable across countries and across

TABLE 1 Cause-of-death groups in the Global Burden of Disease study

Cause group	Major cause categories	International Classification of Diseases	
		ICD-9 codes	ICD-10 codes
Group 1: Communicable, maternal, perinatal, and nutritional diseases	Infectious and parasitic diseases Respiratory infections Maternal conditions Conditions arising during the perinatal period Nutritional deficiencies	001–139, 243, 260–269, 279.5, 280–285, 320–323, 381–382, 460–465, 466, 480–487, 614–616, 630–676, 760–779	A00–B99, G00–G04, N70–N73, J00–J06, J10–J18, J20–J22, H65–H66, O00–O99, P00–P96, E00–E02, E40–E46, E50, D50–D64
Group 2: Noncommunicable diseases	Malignant neoplasms Diabetes mellitus Endocrine disorders Neuro-psychiatric conditions Sense organ diseases Cardiovascular diseases Chronic respiratory diseases Digestive diseases Genito-urinary diseases Skin diseases Musculoskeletal diseases Congenital anomalies Oral conditions	140–242, 244–259, 270–279 (minus 279.5), 286–319, 324–380, 383–459, 470–478, 490–613, 617–629, 680–759	C00–C97, D00–D48, D65–D89, E03–E07, E10–E16, E20–E34, E51–E89, F01–F99, G06–G99, H00–H61, H68–H95, I00–I99, J30–J99, K00–K92, N00–N64, N75–N99, L00–L99, M00–M99, Q00–Q99
Group 3: Injuries	Unintentional injuries Intentional injuries	E800–999	V01–Y98

communities within countries and are therefore separated from the other noncommunicable causes of death in this classification system.

For the cause-of-death models in the Global Burden of Disease study, separate regressions were run for each cause group and for each of 14 age-sex groups,[4] using the following form:

$$\ln M_i = \beta_0 + \beta_1 \ln T_i + \varepsilon_i \qquad (2)$$

where M_i is the mortality rate from the specified cause group in observation i, T_i is the mortality rate from all causes combined, β_0 and β_1 are coefficients to be estimated, and ε_i is an observation-specific error term drawn from a normal distribution with mean 0 and unknown variance to be estimated. In this framework, the mortality rates from Groups 1, 2, and 3 in a given country, year, and age-sex group are assumed to be realizations of three independent normally distributed random processes. The regression results from this model

pointed to a strong association between the level of all-cause mortality and the level of Group 2 mortality and between all-cause mortality and Group 1 mortality in all age groups below 70 years. The predictive power of all-cause mortality for Group 3 mortality was relatively weak.

Limitations of the GBD 90 approach

An important limitation of the standard regression approach used in the Global Burden of Disease study is that it does not recognize two fundamental features of cause-of-death data. Because cause-of-death patterns represent the proportions of all deaths that are attributed to each of a set of mutually exclusive and collectively exhaustive causes or cause groups, this type of data has two basic constraints common to all types of compositional data: (i) the proportion of deaths attributed to each cause must be between 0 and 1; and (ii) the set of proportions for all of the cause groups must sum to unity. In the regression model described above, violations of both constraints are possible. For example, predicted mortality for one cause group may exceed the all-cause mortality rate, thus violating the first constraint. Moreover, because independent regressions are run on each of the three cause groups for the same country-year observation, they are not constrained to sum to the all-cause mortality rate, thus violating the second constraint. In the GBD 90, an additional normalization step was undertaken after the predicted mortality rates were computed in order to impose the second constraint, but the model itself does not take account of the interdependence of the three groups that constitute total mortality.

New models for causes of death

An alternative to the use of independent regression models for each constituent cause group is offered by a class of general statistical models described as compositional models, with applications from a range of disciplines, including political science, geology, and biology (Aitchison 1986; Katz and King 1999). A general statistical model for compositional data has been presented by Katz and King (1999) in an application to multiparty electoral data. The following description of the approach is adapted from their work.

In order to model compositional data with J different cause groups, we first define a vector of cause fractions $P_i = (P_{i1},\ldots,P_{iJ})$ for each observation i. Following Aitchison (1986), the data are modeled using the additive logistic normal distribution. First, a $(J-1)$ vector Y_i is generated by calculating the log ratios of each cause fraction relative to the fraction for cause J:

$$Y_{ij} = \ln\left(\frac{P_{ij}}{P_{iJ}}\right) \tag{3}$$

The vector $Y_i = (Y_{i1},\ldots Y_{i(J-1)})$ is assumed to be multivariate normal with mean vector μ_i and variance matrix Σ_i. The expectation of each log ratio is assumed to be a linear function of the explanatory variables in the model:

$$\mu_{ij} = X_{ij}\beta_j \tag{4}$$

where X_{ij} is a vector of explanatory variables and β_j are parameters to be estimated.

In previous models, only all-cause mortality was used as an explanatory variable. This is consistent with a narrow interpretation of the epidemiologic transition as the changes that occur as mortality rates decline, without reference to the broader context of development within which these health gains are realized. To explore a broader view of the epidemiologic transition that accounts for this developmental context, we have included gross domestic product (GDP) per capita in international dollars as an additional explanatory variable[5] (World Health Organization 2000). The logged form was used for both variables because this formulation tended to provide a better fit than the linear one.

Based on this specification, the multivariate normal model for the log ratios may be expressed as a system of two regression equations[6]:

$$Y_{i1} = \beta_0 + \beta_1 \ln(T_i) + \beta_2 \ln(G_i) + \varepsilon_{i1} \tag{5a}$$

$$Y_{i2} = \gamma_0 + \gamma_1 \ln(T_i) + \gamma_2 \ln(G_i) + \varepsilon_{i2} \tag{5b}$$

where Y_{i1} and Y_{i2} are the log ratios as defined in equation (3), T_i is the all-cause mortality rate, and G_i is GDP per capita. The two residual terms ε_{i1} and ε_{i2} have expectations of 0, variances of σ_1^2 and σ_2^2 respectively, and correlation of ρ.

Maximum likelihood estimates of the model parameters were obtained using the seemingly unrelated regression model (Greene 1993).

Data

Our analysis used the World Health Organization (WHO) database on mortality by cause, coded according to various revisions of the International Classification of Diseases (ICD). This database is based on the annual reporting of vital registration data to WHO by selected countries since 1950. For this analysis, only vital registration data from countries considered to have systems that capture in excess of 95 percent of deaths were included. In all, data from 58 countries for the years 1950 to 1998 were included, totaling 1,576 country-years of observation. Table 2 lists the countries in the dataset and the range of years for each country series. Because the dataset includes only countries with nearly complete vital registration systems re-

TABLE 2 Countries and range of years in database

Country	Years	Country	Years
Albania	1992–93	Latvia	1980–97
Argentina	1966–96*	Lithuania	1987–98
Armenia	1990–97	Luxembourg	1967–97
Australia	1950–95	Macedonia	1992–97
Austria	1955–98	Malta	1965–98*
Azerbaijan	1987–97	Mexico	1958–95*
Belarus	1987–97*	Moldova	1992–96
Belgium	1954–94	Netherlands	1950–97
Bulgaria	1980–97	New Zealand	1950–96
Canada	1950–97	Norway	1951–95
Chile	1955–94*	Poland	1970–96*
Costa Rica	1961–95*	Portugal	1955–98
Croatia	1991–97	Romania	1980–98*
Czech Republic	1986–97	Russian Federation	1989–97
Denmark	1952–96	Singapore	1963–97
Estonia	1987–97	Slovakia	1992–95
Finland	1952–96	Slovenia	1992–97
France	1950–97	Spain	1951–96*
Georgia	1981–90*	Sweden	1951–96
Germany	1990–98	Switzerland	1951–94
Greece	1961–97	Tajikistan	1986–92
Hungary	1960–97	Turkmenistan	1987–94
Iceland	1951–95	Ukraine	1989–97*
Ireland	1950–96	United Kingdom	1950–97
Israel	1975–96	United States	1950–97
Italy	1951–96	Uruguay	1955–90*
Japan	1950–97	Uzbekistan	1992–93
Kazakhstan	1987–97	Venezuela	1955–94*
Kyrgyzstan	1987–98	Yugoslavia	1968–90*

* Excluded years: Argentina 1971–76, 1980–81; Belarus 1991; Chile 1983; Costa Rica 1984; Georgia 1983–84; Malta 1966; Mexico 1984; Poland 1981–82; Romania 1984–88; Spain 1970; Ukraine 1993–95; Uruguay 1961–62, 1979; Venezuela 1984, 1991; Yugoslavia 1971–77

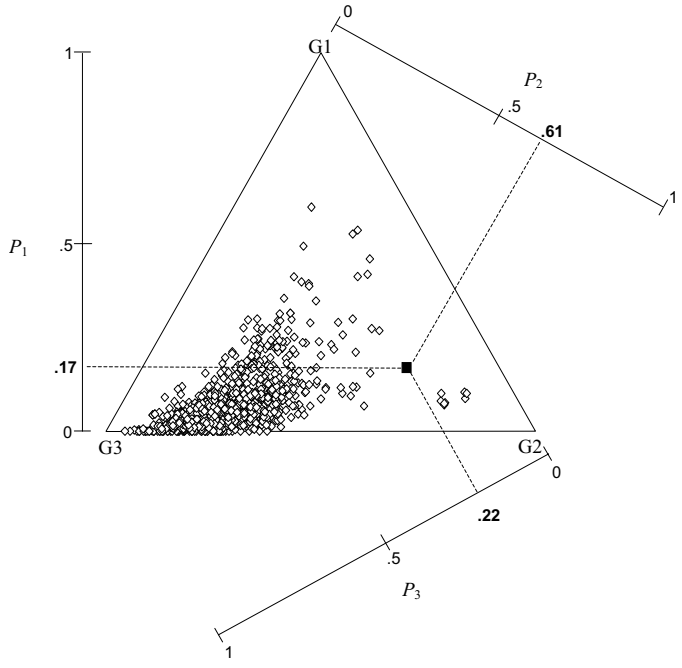
porting to WHO since 1950, the sample is weighted heavily toward countries in Europe but includes some developing countries as well.

Twenty age groups were used in this study: less than 1 month, 1 to 11 months, 1 to 4 years, 5 to 9 years, 10 to 14 years, and so on by five-year age groups, up to 80 to 84 years and 85 years and older. For the two youngest age groups, a smaller number of observations were available because a number of countries over different periods reported only on the age range from birth to 11 months. A total of 586 country-years of observations were available for the first two age groups.

Graphical display of cause-of-death patterns

Given the classification of deaths into Groups 1, 2, and 3, we may represent a range of cause-of-death patterns visually using a ternary diagram, which allows any cause-of-death pattern described in terms of three proportions to be displayed in two dimensions (Katz and King 1999; Cox 2000). Figure 1 presents an example of a ternary diagram on which the data for males ages 20–24 years have been plotted. In this diagram, each point (indicated by a small diamond) represents one country-year of observation, showing the distribution of deaths across Groups 1, 2, and 3. The vertices are labeled as G1 at the top, G2 at the bottom right, and G3 at the bottom left, indicating the three groups. The fraction of deaths attributable to each cause is represented as the perpendicular distance from the side of the triangle opposite the labeled vertex. The nearer a point is to the vertex, the higher the proportion attributable to that cause. For example, a point located near the top vertex would have a very high proportion of Group 1 deaths and low proportions for Groups 2 and 3. A point located along the bottom edge of the triangle has no Group 1 deaths. The point indicated by a bold square in Figure 1 exemplifies a pattern consisting of 17 percent of deaths from Group 1, 61 percent

FIGURE 1 Example of a ternary diagram for the three cause-of-death groups, for males aged 20–24 years



NOTE: For major cause categories of the three cause-of-death groups see Table 1 and discussion in text.

from Group 2, and 22 percent from Group 3. For clarity, we added numbered axes indicating the scales in each dimension and traced the location of the example point on each axis.

Figure 2 presents the entire dataset by age and sex as a series of ternary diagrams. The first block, consisting of four rows of diagrams, is for males, and the second block for females. Each diagram shows the data for one age group, ordered from left to right by row, from ages 0 to 1 month in the top left to ages 85 years and older in the bottom right corner of each four-row block. The least variation in cause-of-death patterns appears among infants, where Group 1 causes dominate in almost all observed data points, and among older adults, where Group 2 dominates. In the age groups from 1 year to around 50 years, there is considerable variation in cause-of-death patterns in both males and females.

Representing the epidemiologic transition

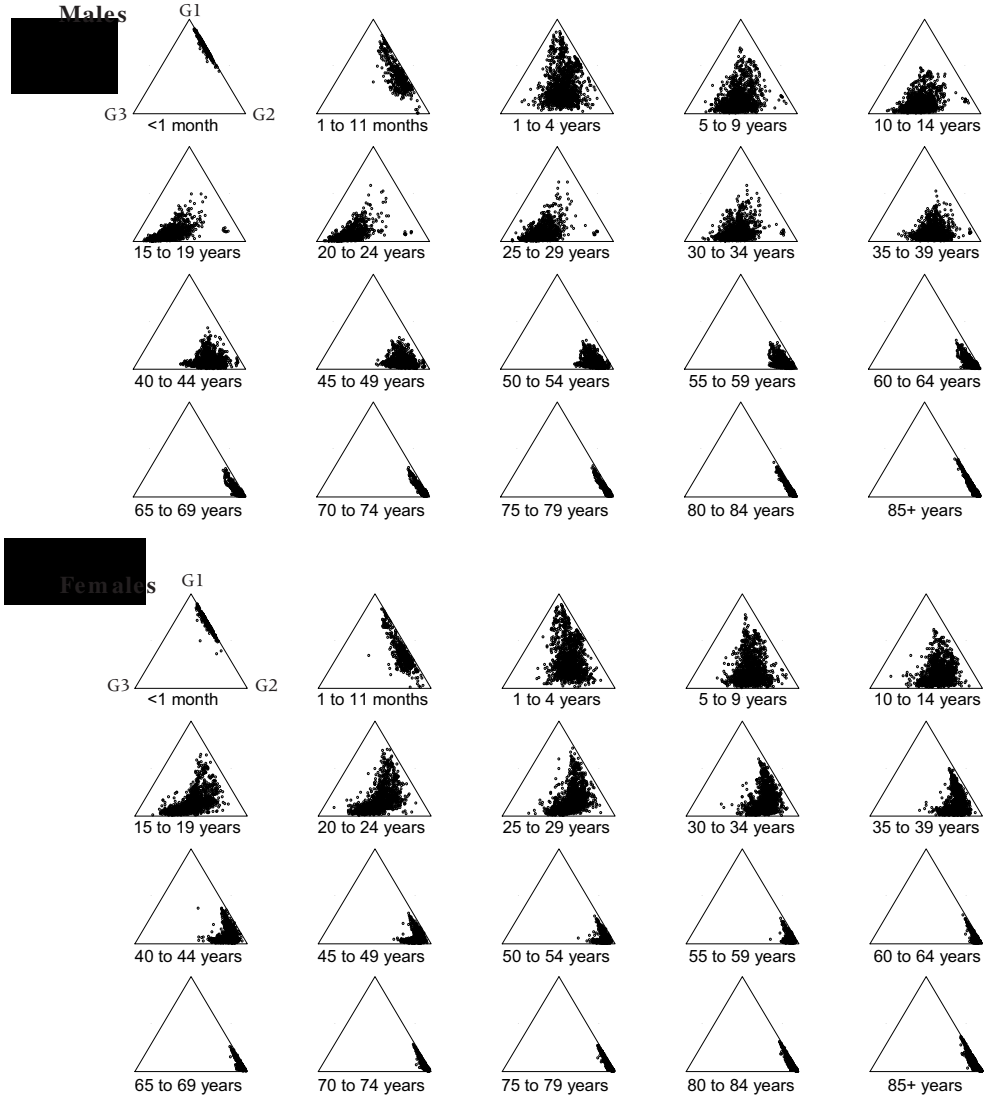
The objective of the regression analysis was to examine the direction and magnitude of changes in cause-of-death patterns as income and mortality change. We used the regression results to predict these changes by extracting the underlying patterns from the fundamental variability, measurement error, and sampling error in the raw data. To identify the independent effects of income and the total mortality level, while at the same time taking advantage of the strong correlation between the two variables, we first developed two sets of predicted income estimates using the empirically observed relationship between income and mortality in our dataset. We ran regressions, for each age-sex group, of the log of income on the log of mortality and found a strong linear relationship. High and low estimates of income were defined, based on these regression results, as the 2.5th and 97.5th percentiles of the predicted distribution of income levels at each level of mortality in the dataset. The result was two sets of predicted incomes that span the range of observed income levels at each mortality level while incorporating the strong correlation between the two variables.

Using the estimated coefficients from the regression results, two sets of predicted values for Y_1 and Y_2 were computed for each observation in the dataset based on the level of all-cause mortality and the two sets of predicted income levels. These Y_1 and Y_2 predictions were then transformed into predicted proportions by cause group using the multivariate logistic transformation:

$$P_j = \frac{\exp\left(Y_j\right)}{1 + \sum_{j=1}^{J-1} \exp\left(Y_j\right)} \tag{6}$$

with P_3 calculated as $1-P_1-P_2$.

FIGURE 2 Ternary diagrams for the three cause-of-death groups by age and sex



NOTE: For major cause categories of the three cause-of-death groups see Table 1 and discussion in text.

These predictions allow us to examine systematic shifts in cause-of-death patterns associated with changes in both mortality levels and income levels while incorporating the strong empirically observed relationship between the two variables.

Results

The theory of the epidemiologic transition suggests that as total mortality declines and income rises, the relative importance of the communicable diseases (Group 1) tends to decrease compared to other causes. The results of this analysis provide a formal, empirical examination of the epidemiologic transition by age and sex and allow us to distinguish between the independent effects of changes in income and total mortality levels.

Table 3 summarizes the regression results for each age and sex group. In most models, the coefficients on both income and total mortality are highly significant. In nearly all cases, increases in income per capita are associated with increases in both Group 2 and Group 3 as proportions of all-cause mortality relative to Group 1 causes. The magnitude of these relative increases tends to be larger for Group 3 than for Group 2, particularly among females, which suggests that the importance of Group 3 causes rises more rapidly than that of Group 2 causes as income rises.

The relationship between cause-of-death patterns and all-cause mortality levels, conditional on income level, is more complicated. For males, lower mortality levels are accompanied by an increase in the importance of Group 2 causes relative to Group 1 causes, while Group 3 tends to become less important than Group 1 in most age groups. For females, on the other hand, both Group 2 and Group 3 tend to gain importance relative to Group 1 as mortality declines.

While the signs and relative magnitudes of the parameter estimates from the regression model offer some insights into the relationships of interest, the most important quantities of interest are the actual predictions of cause-of-death patterns, which are nonlinear functions of these parameters and account for the powerful interactions between changes in income and total mortality.

The predicted trends in cause-of-death patterns are plotted by age and sex in Figure 3. As in Figure 2, the first set of diagrams is for males, and the second set for females, with the diagrams ordered by age within each block. In each diagram, two traces appear, representing a high-income and low-income scenario. The epidemiologic transition may be viewed in each diagram as the path traced by the points as total mortality declines, conditional on either high or low income levels. The difference between the two lines in each graph reflects the independent effect of income additional to the combined effect of income through mortality.

In children, mortality declines are marked by movements from the top of the diagram toward the bottom—in other words, movement away from Group 1 causes toward Group 2 causes. Group 3 causes represent a small proportion of all deaths at the youngest ages, irrespective of either total mortality or income levels. For children above the age of one year, injuries (Group 3) become increasingly important, particularly for males.

TABLE 3 Parameter estimates from seemingly unrelated regression models of log ratios of cause fractions on all-cause mortality (TOT) and GDP

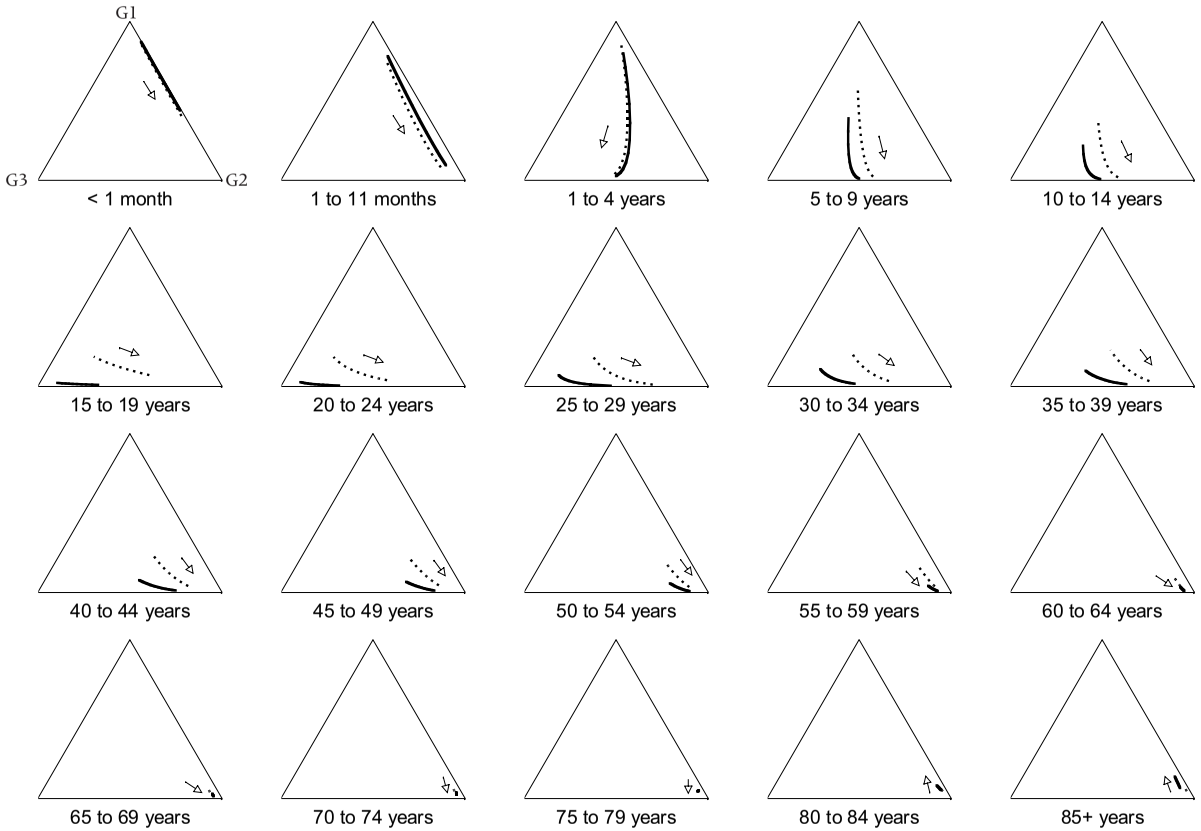
	Coefficients for $\ln(P_3/P_1)$						Coefficients for $\ln(P_2/P_1)$					
Age group	ln(TOT)	p	ln(GDP)	p	Intercept	p	ln(TOT)	p	ln(GDP)	p	Intercept	p
Males												
< 1 month	–0.906	<0.001	–0.662	<0.001	7.664	<0.001	–0.713	<0.001	–0.076	0.010	4.443	<0.001
1–11 months	–0.867	<0.001	–0.356	<0.001	6.806	<0.001	–0.899	<0.001	–0.067	0.163	6.311	<0.001
1–4 years	–0.929	<0.001	0.208	<0.001	2.542	<0.001	–0.764	<0.001	0.227	<0.001	1.961	<0.001
5–9 years	–0.717	<0.001	0.473	<0.001	–0.217	0.713	–0.927	<0.001	0.307	<0.001	2.053	<0.001
10–14 years	–0.585	<0.001	0.515	<0.001	–0.804	0.165	–0.907	<0.001	0.305	<0.001	2.177	<0.001
15–19 years	0.348	<0.001	1.066	<0.001	–8.732	<0.001	–0.458	<0.001	0.542	<0.001	–1.128	0.006
20–24 years	0.229	0.001	1.001	<0.001	–7.458	<0.001	–0.604	<0.001	0.500	<0.001	0.217	0.645
25–29 years	–0.061	0.399	0.672	<0.001	–3.413	<0.001	–0.812	<0.001	0.197	<0.001	4.061	<0.001
30–34 years	–0.069	0.338	0.576	<0.001	–2.867	<0.001	–0.742	<0.001	0.158	<0.001	4.269	<0.001
35–39 years	0.096	0.138	0.680	<0.001	–4.984	<0.001	–0.491	<0.001	0.343	<0.001	1.676	0.007
40–44 years	0.308	<0.001	0.812	<0.001	–7.726	<0.001	–0.238	<0.001	0.553	<0.001	–1.235	0.041
45–49 years	0.365	<0.001	0.809	<0.001	–8.453	<0.001	–0.152	0.007	0.644	<0.001	–2.238	<0.001
50–54 years	0.337	<0.001	0.765	<0.001	–8.291	<0.001	–0.070	0.259	0.700	<0.001	–3.015	<0.001
55–59 years	0.256	0.001	0.687	<0.001	–7.425	<0.001	0.001	0.985	0.708	<0.001	–3.402	<0.001
60–64 years	0.112	0.190	0.523	<0.001	–5.272	<0.001	0.079	0.332	0.604	<0.001	–2.958	<0.001
65–59 years	0.028	0.775	0.378	<0.001	–3.668	<0.001	0.165	0.079	0.472	<0.001	–2.485	0.010
70–74 years	–0.088	0.422	0.213	<0.001	–1.538	0.176	0.094	0.369	0.252	<0.001	–0.037	0.973
75–79 years	–0.247	0.054	0.079	0.036	0.865	0.523	–0.054	0.657	0.007	0.840	3.343	0.009
80–84 years	0.114	0.413	0.035	0.387	–2.263	0.133	0.113	0.398	–0.183	<0.001	3.345	0.021
85+ years	0.454	0.001	0.006	0.876	–5.740	<0.001	0.133	0.333	–0.403	<0.001	4.482	0.001

Age group	Coefficients for $\ln(P_3/P_1)$						Coefficients for $\ln(P_2/P_1)$					
	ln(TOT)	p	ln(GDP)	p	Intercept	p	ln(TOT)	p	ln(GDP)	p	Intercept	p
Females												
< 1 month	–0.949	<0.001	–0.732	<0.001	8.524	<0.001	–0.732	<0.001	–0.089	0.004	4.600	<0.001
1–11 months	–0.932	<0.001	–0.315	<0.001	6.680	<0.001	–0.981	<0.001	–0.061	0.210	6.726	<0.001
1–4 years	–1.027	<0.001	0.061	0.106	3.882	<0.001	–0.770	<0.001	0.248	<0.001	1.667	<0.001
5–9 years	–1.005	<0.001	0.341	<0.001	1.179	0.023	–0.962	<0.001	0.304	<0.001	1.783	<0.001
10–14 years	–1.129	<0.001	0.396	<0.001	1.006	0.054	–0.995	<0.001	0.234	<0.001	2.624	<0.001
15–19 years	–1.036	<0.001	0.849	<0.001	–2.378	<0.001	–1.045	<0.001	0.287	<0.001	2.826	<0.001
20–24 years	–1.383	<0.001	0.738	<0.001	–0.051	0.927	–1.204	<0.001	0.212	<0.001	4.227	<0.001
25–29 years	–1.607	<0.001	0.422	<0.001	3.681	<0.001	–1.305	<0.001	0.038	0.230	6.561	<0.001
30–34 years	–1.807	<0.001	0.308	<0.001	5.978	<0.001	–1.440	<0.001	0.033	0.328	7.929	<0.001
35–39 years	–1.719	<0.001	0.404	<0.001	5.394	<0.001	–1.444	<0.001	0.160	<0.001	7.778	<0.001
40–44 years	–1.532	<0.001	0.505	<0.001	4.216	<0.001	–1.344	<0.001	0.262	<0.001	7.371	<0.001
45–49 years	–1.280	<0.001	0.503	<0.001	3.471	<0.001	–1.175	<0.001	0.278	<0.001	7.214	<0.001
50–54 years	–1.440	<0.001	0.360	<0.001	6.186	<0.001	–1.182	<0.001	0.198	<0.001	8.682	<0.001
55–59 years	–1.314	<0.001	0.290	<0.001	6.336	<0.001	–1.019	<0.001	0.150	<0.001	8.610	<0.001
60–64 years	–1.484	<0.001	0.079	0.072	9.765	<0.001	–1.079	<0.001	0.012	0.743	10.802	<0.001
65–59 years	–1.418	<0.001	<0.001	0.992	10.447	<0.001	–1.060	<0.001	–0.101	0.010	12.194	<0.001
70–74 years	–1.129	<0.001	–0.041	0.389	9.016	<0.001	–1.000	<0.001	–0.229	<0.001	13.353	<0.001
75–79 years	–0.611	<0.001	0.016	0.742	4.446	0.001	–0.930	<0.001	–0.361	<0.001	14.346	<0.001
80–84 years	0.140	0.307	0.168	0.001	–3.645	0.021	–0.616	<0.001	–0.405	<0.001	12.198	<0.001
85+ years	0.826	<0.001	0.262	<0.001	–11.578	<0.001	–0.086	0.585	–0.482	<0.001	7.796	<0.001

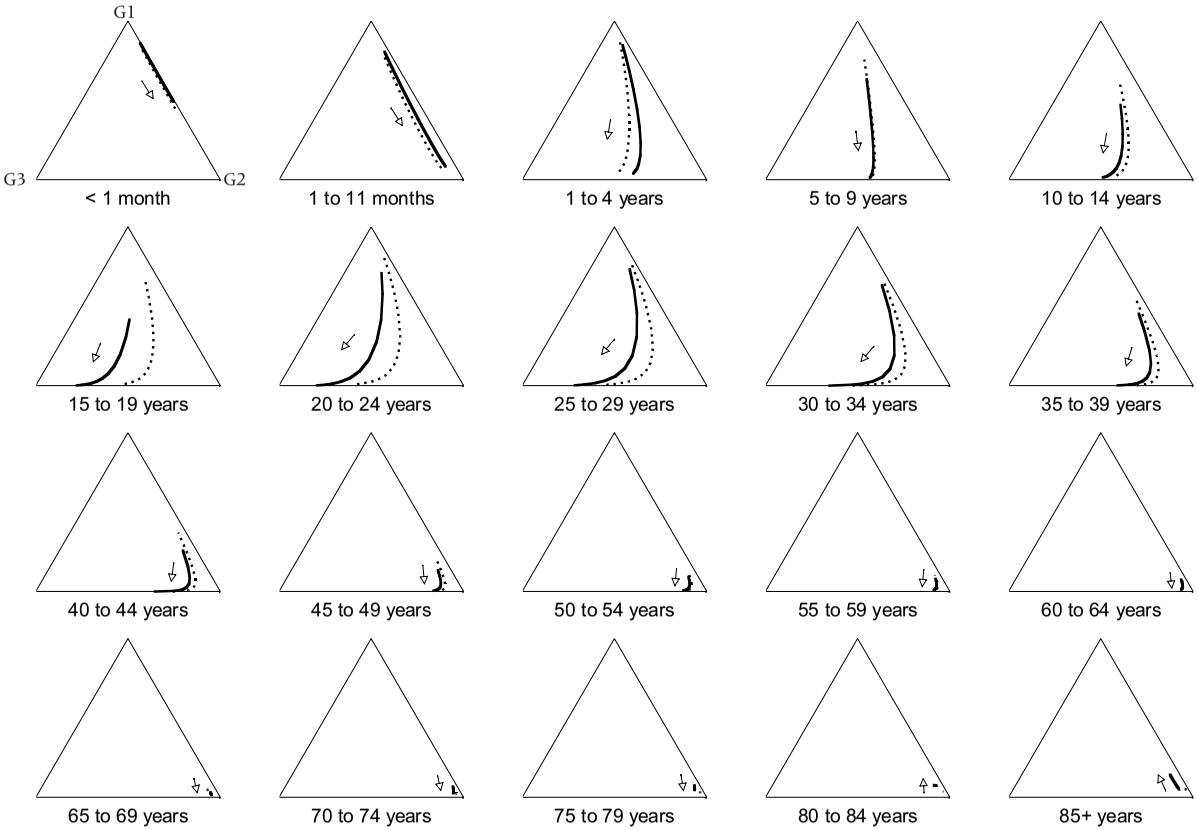
NOTE: P_1, P_2, and P_3 are the proportions of all deaths from Groups 1, 2, and 3, respectively.

FIGURE 3 Ternary diagrams of the epidemiologic transition by age and sex: Solid lines depict the high-income scenario and dotted lines depict the low-income scenario; arrows indicate the direction of decreasing total mortality

Males



Females



NOTE: For major cause categories of the three cause-of-death groups see Table 1 and discussion in text.

For young and middle-aged adult males, depicted in the second and third rows in Figure 3, the mortality transition follows a path from left to right, indicating an increase in noncommunicable diseases relative to injuries as mortality decreases. This trend occurs at both low and high levels of income. Interestingly, for young adult females, the transition moves first from Group 1 to Group 2 as maternal conditions decline as important causes of death, but then from Group 2 to Group 3 as both infectious and chronic causes of death decline more rapidly than injuries. An inspection of the original data upon which these models are based indicates that mortality rates from all three groups tend to decline in males and females as overall mortality declines, so that the difference between males and females relates to the *relative* pace of the decline in the different cause categories. In young adult males, Group 3 causes decline most rapidly as overall mortality declines, followed by Group 1 and then Group 2. For young adult females, on the other hand, Group 1 causes decline most rapidly, and Group 3 causes decline at the slowest pace. While there is some variation by sex in the relative importance of specific causes of death within Group 3—for example, accidents are more important for females, while suicide and homicide are more important for males—the sex differences in the trends displayed in Figure 3 do not appear to be related to these more detailed causes.

At the oldest age groups, there is little evidence of the epidemiologic transition despite major declines in levels of old-age mortality (Vaupel 1997). In both sexes, noncommunicable diseases dominate at all levels of mortality represented in the dataset. This finding is consistent with the hypothesis of Olshansky and Ault (1986), who postulated a fourth stage of the epidemiologic transition consisting of delayed degenerative diseases. This fourth stage is marked by a shift in mortality toward older ages in concert with stability in the pattern of causes of deaths.

The income effect is most notable between ages 15 and 34 in females, while for males the income effect starts as early as age 5 and continues through the age group 40–44. For adults of both sexes, higher income levels are associated with higher contributions from injuries. For males, the increase in Group 3 draws from both Groups 1 and 2, while for females the rise in Group 3 is accompanied mostly by a drop in Group 2 causes. Rising income, conditional on a particular mortality level, leads to a decrease in the relative importance of injuries in children below age 5, while at all other ages for which the income effect is significant, the direction of the effect is the opposite.

Discussion

Omran's theory of the epidemiologic transition has had a penetrating influence on thinking about systematic changes in patterns of disease and mor-

tality. Historical analysis of the epidemiologic transition has focused primarily on the first half of the twentieth century (Vallin and Meslé 1988). In this article, we examined trends in cause-of-death patterns by age and sex since 1950, in consideration of the epidemiologic transition as a durable framework for describing relationships between levels of mortality and the relative importance of its constituent causes.

Our analysis used the most extensive available cause-of-death database coded according to the International Classification of Diseases, as well as new statistical models for causes of death that overcome some of the limitations of previous models. While the data show considerable variation in cause-of-death patterns across countries and over time, the models reveal powerful empirical regularities relating variation in mortality rates from all causes to the relative contributions of communicable diseases, noncommunicable diseases, and injuries.

The results of these analyses confirm that as all-cause mortality declines, the composition of mortality by cause changes systematically in many age groups. The epidemiologic transition is not simply the result of changing age structure in the population but a real transition in the cause composition of age-specific mortality. While our analysis confirms the general principles of the epidemiologic transition, different patterns by age and sex are worth emphasizing.

1) In children under 1 year, the epidemiologic transition produces a shift from Group 1 causes to Group 2 causes, with little or no role played by injuries regardless of the level of all-cause mortality. The transition at this age is the same for males and females and is not influenced by income independently from all-cause mortality levels.

2) In children over age 1 year, the transition is from Group 1 causes to a nearly equal mix of Group 2 and Group 3 causes. The more dominant role of injuries in males as compared to females becomes evident as early as age 5.

3) In the young adult age groups, 15–44 years, the epidemiologic transition is notably different for males and females. In particular, the independent effects of income changes and mortality changes emerge as distinct patterns in males and females. For males, decreases in overall mortality lead predominantly to a shift from injuries to noncommunicable diseases, while rising income produces the opposite effect. For females, mortality declines produce first a rise in the importance of Group 2 conditions, followed by a fall in Group 2 as Group 3 causes grow in importance. Rising income further emphasizes the shift from noncommunicable conditions to injuries in females.

4) In males and females over age 50, the epidemiologic transition produces almost no change in the cause composition of mortality. In other words, age-specific mortality rates from Groups 1, 2, and 3 are almost entirely a function of the all-cause mortality rates for those age groups.

The regularity of the epidemiologic transition is the basis for using cause-of-death models to aid in the estimation of age- and cause-specific mortality rates in developing countries without complete vital registration systems. This analysis suggests that most of the change in the cause structure of mortality occurs among children and young adults. It is in these age groups that efforts to collect new information through sample registration systems, surveys using verbal autopsy, and the expansion of vital registration will improve cause-of-death estimation. In older adults, our analysis supports the notion of a fourth stage of transition proposed by Olshansky and Ault (1986), in which the cause composition of mortality remains stable but deaths shift to older ages.

The model results for adult females offer an interesting empirical illustration of the "double burden" phenomenon proposed by Frenk and colleagues (1991). In many societies, heterogeneity in the pace of the epidemiologic transition among different social strata or geographic regions produces a "protracted and polarized" transition model marked by overlap between stages. As a result, the interim stage of the transition at the aggregate level is characterized by high levels of both Group 1 and Group 2 causes. In females, the bow-shaped curve at young adult ages (as causes of death shift toward Group 2 and then Group 3) suggests that in countries with subgroups experiencing much higher mortality than other groups, a nearly equal mix of Groups 1 and 2 is possible during the intermediate phase of transition. The potential for an equal mix of Groups 1 and 2 is smaller for males, as indicated by the curves in Figure 3.

Because our dataset includes only countries where vital registration coverage is nearly complete, the analyses do not reflect patterns in countries with the highest mortality levels. Generalization of our results to high-mortality patterns must therefore be undertaken with caution. Nevertheless, we believe that the patterns that emerge from this analysis offer insights into the epidemiologic transition from high-mortality to low-mortality settings. Indeed, we observe that the general theory of the transition that has been applied most frequently to changes that occurred during the first half of the twentieth century also provides a powerful analytical framework for understanding systematic shifts that occurred in the second half. It will be useful to extend the analyses presented here to include longer time-series data on causes of death in such countries as France and the Netherlands (e.g., Vallin and Meslé 1988; Wolleswinkel-van den Bosch et al. 1997) in order to examine more closely the relationship between trends in the first and second halves of the century.

One substantive limitation of the database and the models of the epidemiologic transition derived from its analysis is the limited number of country-years of observation that reflect moderate to severe HIV epidemics. Clearly, in regions such as sub-Saharan Africa, where the HIV epidemic has

led to more than a doubling of the risks of adult mortality (World Health Organization 2000), the cause composition of young adult males and females will shift dramatically toward Group 1. Unfortunately, very few communities with large HIV epidemics have complete vital registration data. Quantification of the effect of the HIV epidemic on the patterns of the epidemiologic transition must await better information on cause-of-death patterns from these settings.

More generally, questions remain regarding patterns of deviation from the typical scheme of the transition. Further efforts must be made to investigate systematic distortions of the general transition pattern, for example in countries of Eastern Europe experiencing a rise in adult mortality rates during the last decade. As emerging health threats provide both large and small examples of reverse transitions, it will be important to continue to revisit the theory of the epidemiologic transition.

Notes

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1 There has been considerable interest in investigating deviations from the general pattern of the epidemiologic transition. For example, the General Conference of the International Union for the Scientific Study of Population, in Brazil in August 2001, included a session on emerging health threats that focused on "unexpected unfavorable trends" in population health.

2 In fact, the re-estimated slopes were surprisingly steep (cardiovascular diseases now had a positive slope of 0.24 to 0.25). Preston at the time noted the counterintuitive interpretation of this result, remarking that the "somewhat unusual suggestion, based on a variety of indirect evidence, is that cardiovascular diseases have in general been important contributors to mortality change, more important than the specific infectious diseases of childhood exclusive of tuberculosis" (Preston 1976: 7).

3 These analyses used Preston's original equation for cardiovascular diseases without adjusting for misclassified deaths in the category "other or unknown" and therefore predicted rising rather than falling cardiovascular disease mortality rates.

4 The seven age groups used were 0 to 4 years, 5 to 14 years, 15 to 29 years, 30 to 44 years, 45 to 59 years, 60 to 69 years, and 70 years and older.

5 We used annual GDP series developed at the World Health Organization based on existing data series from the United Nations, International Monetary Fund, World Bank, and Organisation for Economic Co-operation and Development. The GDP series were converted to international dollars using purchasing power parity ratios estimated on the basis of price comparison studies where available, or using GDP per capita in United States dollars, United Nations post-adjustment multipliers, and other geographic dummy variables for other countries. Extrapolations of some series were made using real GDP growth rates adjusted for inflation using United States GDP deflators.

6 The results of the analysis do not depend on the particular choice of reference cause group, so that Y_1 and Y_2 may be defined in terms of any pair of cause groups relative to the third group. We have chosen Group 1 as the reference group for ease of exposition, and results in Table 3 therefore refer to Y_1 as the log of the Group 3 to Group 1 ratio and Y_2 as the log of the Group 2 to Group 1 ratio.

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